Chapter 6
Understanding Landscapes Through Spatial Modeling

Michael C. Wimberly, Stephen P. Boyte, and Eric J. Gustafson

6.1 Introduction

Ecological restoration is defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Society for Ecological Restoration International Science and Policy Working Group 2004). Restoration thus entails the identification of a reference ecosystem to serve as a benchmark and the implementation of management practices that move the forest toward a set of desired future conditions. Expanding the scale of forest restoration from individual stands to broader landscapes presents several challenges. The reference ecosystem concept must be extended to encompass reference landscapes consisting of multiple forest types and successional stages. Because of the pervasive influence of human land use, it is often difficult, if not impossible, to identify modern landscapes that can provide suitable benchmarks. Furthermore, scientists and managers often lack a clear understanding of how proposed restoration activities will impact disturbance regimes and forest succession across broad geographic areas. Because of these knowledge gaps, there is often considerable uncertainty about what the desired outcome of forest landscape restoration should be and whether management activities will actually move the landscape toward the desired state.

Forest landscapes encompass heterogeneous mosaics of physical environments, community types, disturbance histories, and land ownerships. Hierarchy theory posits that rates of change decrease with increasing spatial extent in ecological

M.C. Wimberly (✉) • S.P. Boyte
Geographic Information Science Center of Excellence,
South Dakota State University Brookings, SD 57006, USA
e-mail: michael.wimberly@sdstate.edu

E.J. Gustafson
USDA Forest Service Northern Research Station, Institute for Applied Ecosystem Studies,
Rhinelander, WI 54501, USA

J. Stanturf et al. (eds.), *Forest Landscape Restoration: Integrating Natural and Social Sciences*, World Forests 15, DOI 10.1007/978-94-007-5326-6_6,

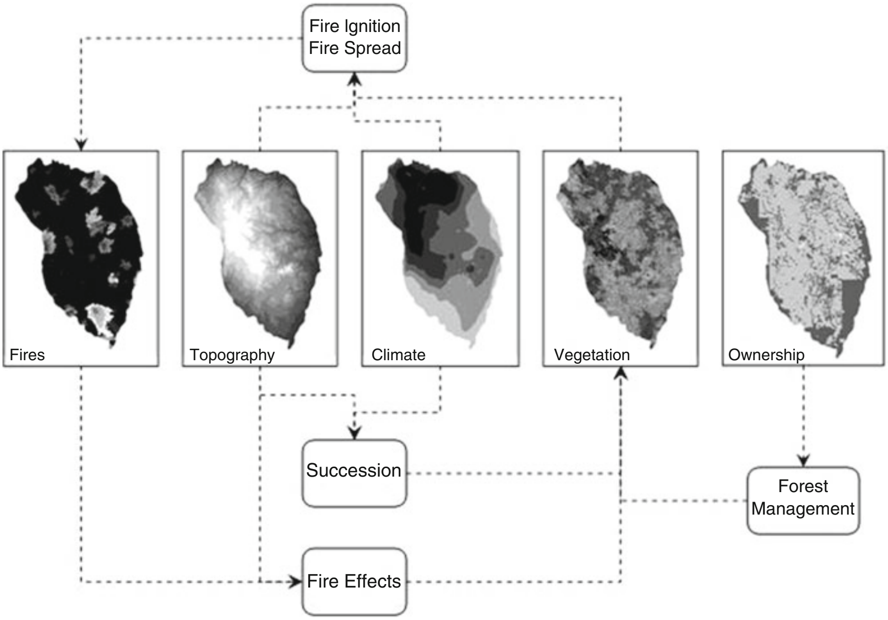

Fig. 6.1 Major landscape patterns and process simulated in forest landscape models. The physical environment and vegetation patterns influence the initiation and spread of wildfires and other natural disturbances. The physical environment also influences fire effects on vegetation and pathways of forest succession. Land ownership is a major driver of forest management practices, which in turn influence vegetation patterns

systems (Urban et al. 1987). Therefore, large landscapes must be studied over temporal extents ranging from decades to centuries. These broad spatial and temporal scales limit our ability to use traditional experimental and observational methods to study forest landscapes. In some cases, historical datasets can be used to study landscape changes (e.g., Wimberly and Ohmann 2004). However, simply extrapolating past trends into the future is problematic because future landscape changes are likely to occur in the context of climates, species assemblages, and socio-economic conditions that have no historical analogues (Hobbs et al. 2006). Despite our limited knowledge of landscape dynamics, land managers must still make decisions that will influence future forest landscapes for decades to centuries. For these reasons, landscape simulation models are increasingly being used for scientific research in the field of landscape ecology and as decision support tools to assist in the practice of forest landscape restoration.

Most forest landscape simulation models currently in use are spatially explicit, with discrete landscape units represented as spatial data structures such as raster cells or vector polygons (Fig. 6.1). The forest vegetation within each landscape unit is characterized by one or more variables such as dominant species, stand age, successional stage, or specific stand structure measurements such as tree size and density. Mathematical or rule-based algorithms are applied to model successional changes

in forest vegetation. Disturbance processes such as fire, windstorms, insects, and timber harvesting change forest vegetation and are also constrained by the spatial pattern of forest vegetation. Spatial relationships are explicitly modeled. They include vertical interactions among climate, topography, soils, and vegetation within landscape units and horizontal interactions such as seed dispersal and fire spread between landscape units and adjacency constraints on timber harvests. Given an initial landscape condition, landscape simulation models generate projections of landscape dynamics that reflect the underlying data and assumptions used to specify the model and estimate parameters.

Several papers have reviewed different types of landscape models, focusing on conceptual and technical aspects of model design (Baker 1989; Keane et al. 2004; Perry and Enright 2006; Scheller and Mladenoff 2007; He 2008). In contrast, this review will examine *how* landscape models are applied in science and management. It will focus on three major applications of landscape simulation models in the field of forest landscape restoration. The first application involves using landscape models to reconstruct historical reference landscapes based on the characteristics of historical disturbance regimes. The second application uses simulation models to project forest landscape change to evaluate the potential effectiveness of forest restoration strategies. The third example applies landscape models in an exploratory framework to expand our understanding of the process of landscape change in disturbed landscapes. The three approaches will be illustrated using examples taken primarily from studies focusing primarily on the effects of timber harvesting and wildfire in temperature forests in North America. However, we also note that forest landscape models can incorporate other disturbances such as insect outbreaks (Cairns et al. 2008) and windstorms (Scheller and Mladenoff 2005; Shifley et al. 2006), and are applied globally in locations ranging from Europe (Schumacher and Bugmann 2006), to China (Bu et al. 2008; Leng et al. 2008), to Australia (Perry and Enright 2002).

6.2 Simulating Historical Reference Landscapes

Forest landscape restoration is predicated on our ability to define reference conditions to serve as benchmarks for restoration. However, because most forest landscapes are dynamic, mosaics of different forest types and successional stages, static reference conditions are often inappropriate. Therefore, the concept of a natural or historical range of variability (HRV) has emerged as a framework for land management and forest restoration (Hunter 1993; Landres et al. 1999; Allen et al. 2002). At the simplest level, the HRV concept can be implemented by defining a range or probability distribution of the relative amounts of different successional stages under the historical disturbance regime. More sophisticated assessments of HRV may also consider the spatial arrangement of successional stages across the landscape. An important implication of the HRV concept is that there is no single "correct" reference condition at the landscape scale. Instead, there may be a variety of potential restoration targets that fall within the HRV.

Although historical data can be used to reconstruct reference landscapes, “snapshots” of landscape characteristics at a single point in time are usually not sufficient for understanding the dynamics of historical landscape conditions in forest ecosystems impacted by wildfires, insect outbreaks, floods, windstorms, and other large-scale disturbances. Simulation models can be used to link data on the rates, sizes, and effects of historical disturbances with knowledge of forest succession to estimate the composition and configuration of forest landscape mosaics. Thus, the application of landscape models to simulate historical reference conditions is primarily a “predictive” approach to landscape modeling rather than an “explanatory” approach (Peck 2004; Perry and Millington 2008). However, explanation of the underlying ecological phenomena is often an important secondary goal, in which techniques such as sensitivity analysis and uncertainty analysis can be applied to examine the influences of model parameters and processes on simulated landscape dynamics (Wimberly 2004; Wimberly and Kennedy 2008).

6.2.1 HRV of Old-Growth Forests in the Oregon Coast Range

In coastal Douglas-fir forests of the Pacific Northwest, forest management controversies have focused on the logging of old-growth forests, the resulting fragmentation of the remaining old growth, and the effects that these changes have had on threatened and endangered species such as the northern spotted owl, marbled murrelet, and Pacific salmon. These concerns eventually led to the development of the Northwest Forest Plan (Forest Ecosystem Management and Assessment Team (FEMAT) 1993). A key component of this plan is a network of reserves where management objectives focus on the development and maintenance of late-successional habitat conditions. However, there has also been growing recognition that wildfires occurred for millennia prior to human settlement in coastal Douglas-fir forests, and that these historical fire regimes encompassed a wide range of fire frequencies, severities, and spatial patterns (Long et al. 1998; Long and Whitlock 2002; Weisberg and Swanson 2003). This evidence of historical wildfires has raised fundamental questions about more recent declines in old growth. Are the current low levels of old-growth forests really an unprecedented effect of logging and other human activities? Or is it possible that old growth was actually an uncommon and highly variable component of the pre-settlement landscape?.

To address these questions, the LAndscape Dynamics Simulator (LADS) was developed to estimate the range of historical variability in the amount and spatial pattern of old-growth forests (Wimberly et al. 2000; Wimberly 2002). Prior to Euro-American settlement, the Oregon Coast Range was characterized by a gradient of disturbance regimes, ranging from large, infrequent, stand-replacing wildfires in the North and along the coast to smaller, more frequent, mixed-severity wildfires to the South and in the interior. Data on historical fire return intervals, severities, and sizes was obtained from dendro-ecological (Impara 1997), paleo-ecological (Long et al. 1998; Long and Whitlock 2002), and historical (Teensma et al. 1991) studies. These data were input into the LADS model to simulate the occurrence and spread

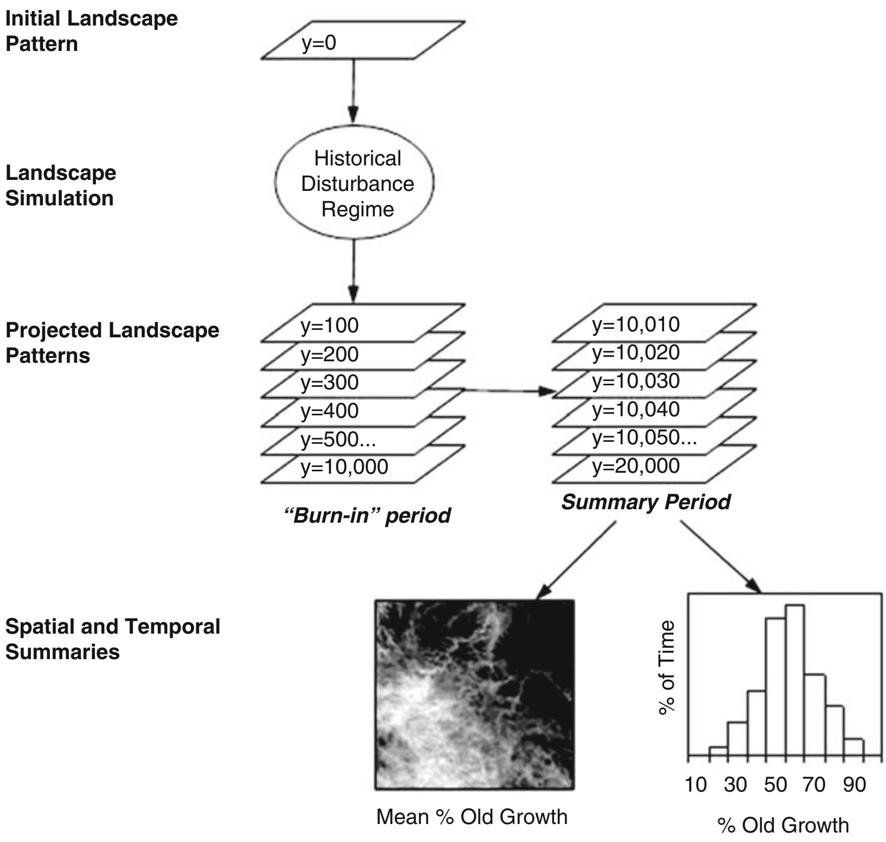

Fig. 6.2 Flowchart illustrating the process of HRV simulation. A landscape simulation model is used to simulate a time series of landscapes using parameters based on the pre-settlement disturbance regime. Following a "burn-in" period in which the simulated landscape patterns overwrite the arbitrary initial conditions, spatial and temporal variability is summarized using a variety of methods

of wildfires, the effects of these fires on forest vegetation, and the pathways of forest succession that occur after wildfires. By running a large number of model simulations, it was possible to translate available information about the historical disturbance regime into estimated probability distributions of the relative abundances old growth and other successional stages (Fig. 6.2).

The results of simulation studies using the LADS model have demonstrated that present-day forest patterns in the Oregon Coast Range are far outside the range of historical variability (Wimberly et al. 2000, 2004; Wimberly 2002). In the historical simulations, old-growth forests occupied an average of ~45% of the Coast Range, but were highly variable in both space and time (Fig. 6.3). Even after accounting for disturbance-driven temporal variability, current amounts of old growth (less than 2% of the landscape) are much lower than would be expected under the pre-settlement disturbance regime (Wimberly et al. 2004).

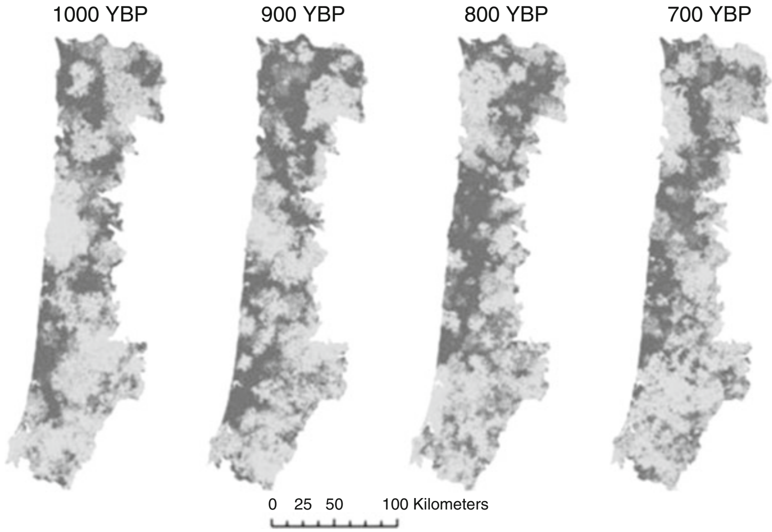

Fig. 6.3 LADS simulation of one hypothetical time series of historical landscape patterns in the Oregon Coast Range. *Dark gray* patches represent closed-canopy old-growth forests. *Light gray* patches represent other forest structure classes (including early-successional, young, and mature forests)

Two major changes to the regional pattern of forest successional stages were also evident. First, there was a shift from a historical landscape that was usually dominated by at least one large (>400,000 ha) patch of old growth to a modern landscape in which old growth mostly occurs in much smaller fragments. Second, there was also a decrease in the total number of small, old-growth patches from the historical landscape to the present. Whereas historical landscapes often had many small remnant old-growth patches embedded in areas of younger forest, there are large portions of the current landscape that are highly isolated from the nearest old-growth patch (Wimberly 2002; Wimberly et al. 2004).

6.2.2 Modeling Landscape Departure from Historical Reference Conditions

Landscape changes in the Oregon Coast Range and other areas of the coastal Pacific Northwest have occurred because the historical disturbance regime of relatively infrequent, large wildfires has been replaced by a forest management regime dominated by smaller and more frequent clearcuts (Wimberly et al. 2004). In contrast, many forests in the interior West had historical disturbance regimes characterized by frequent fires that maintained fuel loads at relatively low levels, leading to a fire regime dominated by patchy, low-severity fires. In the current landscape, fire

suppression, selective logging, and grazing have contributed to a more homogeneous landscape of dense forests and high fuel loads, increasing the potential for uncharacteristically large and severe wildfires (Hessburg et al. 2005). The National Fire Plan, which is aimed at reducing the risk of wildfire and restoring forest health, is applying HRV concepts to support fire and fuels management (Keane et al. 2007). The prioritization of forest management activities is being based in part on the assignment of a fire regime condition class (FRCC), which assesses the degree to which the current fire regime, fuel loads, and vegetation structure differ from the conditions that occurred under the historical fire regime (Schmidt et al. 2002).

The LANDSUM model was developed as part of the larger LANDFIRE project to serve as a tool for modeling the spatial distribution of fire regimes and the resulting vegetation patterns across heterogeneous forest landscapes (Keane et al. 2006). The goals of the LANDFIRE project are to provide digital maps and datasets characterizing vegetation, fuels, and fire regimes across the United States (Rollins and Frame 2006). Two of the national products being developed by LANDFIRE are the FRCC product and the FRCC departure index product. To produce these products, the LANDSUM model is used to simulate a probability distribution of historical reference conditions under the pre-settlement fire regime, and this simulated HRV is compared with the current landscape conditions (Keane et al. 2007). These comparisons are made at the scale of relatively small (e.g., 81 ha) landscape reporting units, which allows the resulting departure from historical reference conditions to be mapped across the landscape to identify specific areas of high departure from the HRV (Karau and Keane 2007).

Although LADS and LANDSUM were both developed to carry out HRV simulation modeling and are conceptually similar in many respects, each was developed with a different application in mind. LADS was originally developed for use in regional ecosystem assessments. Therefore, many fine-scale details were sacrificed to produce a model that could efficiently simulate large areas (millions of ha) over long time frames (thousands of years) on a single-processor desktop computer. Results from LADS have primarily been used as baselines for broad-scale comparison with current and projected future landscape conditions when conducting regional assessments of forest policy (Nonaka and Spies 2005; Thompson et al. 2006; Nonaka et al. 2007; Spies et al. 2007b).

In contrast, LANDSUM is more focused on making landscape-level assessments (simulation areas encompassing tens of thousands of hectares), with more emphasis on capturing relevant local variability in the environment and the resulting spatial patterns of fire and vegetation (Keane et al. 2002; Karau and Keane 2007). This greater emphasis on local detail is necessary to support the goal of using LANDSUM to map the spatial patterns of deviation from historical reference conditions, and ultimately to apply the resulting information to help prioritize fuels management activities (Keane et al. 2007). To this end, an accompanying set of analytical tools and methods has been developed for quantifying the departure of current conditions from the modeled HRV (Steele et al. 2006). However, the cost of this additional complexity is high computational demand, necessitating the use of parallel processing to carry out simulations at regional to national levels.

6.3 Projecting Future Landscape Changes

Scenario-based landscape modeling has proven to be a valuable tool for forest planning and environmental assessment. This approach involves developing a limited set of alternative future scenarios (usually 2–6) that encompass projections of future landscape conditions based on a set of assumptions about land management policies and the resulting environmental changes (Peterson et al. 2003; Nassauer and Corry 2004). These hypothetical but plausible futures are intended to serve as structured narratives that outline the range of uncertainty about what the future may bring. Spatial simulation models are often applied as tools to project the changes in forest landscape pattern that will occur under alternative forest management scenarios. A frequent goal of these assessments is to contrast the future landscape conditions resulting from a continuation of current management practices with various alternatives strategies that aim to restore the forest landscape to a set of desired future conditions (Fig. 6.4).

These applications of landscape simulation models can be viewed as a hybrid of the predictive and explanatory modeling approaches (Peck 2004; Perry and Millington 2008). They are predictive in that the scenarios are developed for real landscapes using a realistic set of alternative management strategies with an underlying objective of projecting future landscape conditions under the alternative scenarios. However, there is typically not an expectation that the models will predict the details of future landscapes with high accuracy or precision. Instead, the emphasis is typically on comparing and contrasting the results of the alternative scenarios to gain an understanding of the relative effects of alternative forest restoration strategies. In this context, the model application can be also viewed as a heuristic exercise in which a major goal is to gain insights into how the interactions of forest restoration activities with ecological processes lead to different trajectories of future landscape change.

6.3.1 Alternative Forest Policies in the Oregon Coast Range

The Coastal Landscape Modeling and Assessment (CLAMS) project used a model called the Landscape Management Policy Simulator (LAMPS) to project regional changes under alternative policy scenarios (Johnson et al. 2007). Policy simulations accounted for different management practices in major land ownership classes, including federal forests managed by the USDA Forest Service and the Bureau of Land Management, state forests managed by the Oregon Department of Forestry, and private forests owned by the forest industry and nonindustrial private landowners. A unique characteristic of the LAMPS model, compared to most other forest landscape simulators, is that it can simulate forest dynamics over extremely large areas (millions of hectares) while at the same time providing extremely detailed information about forest conditions (individual tree lists for each forest stand) (Bettinger et al. 2005). Under each policy scenario, the LAMPS model accounts

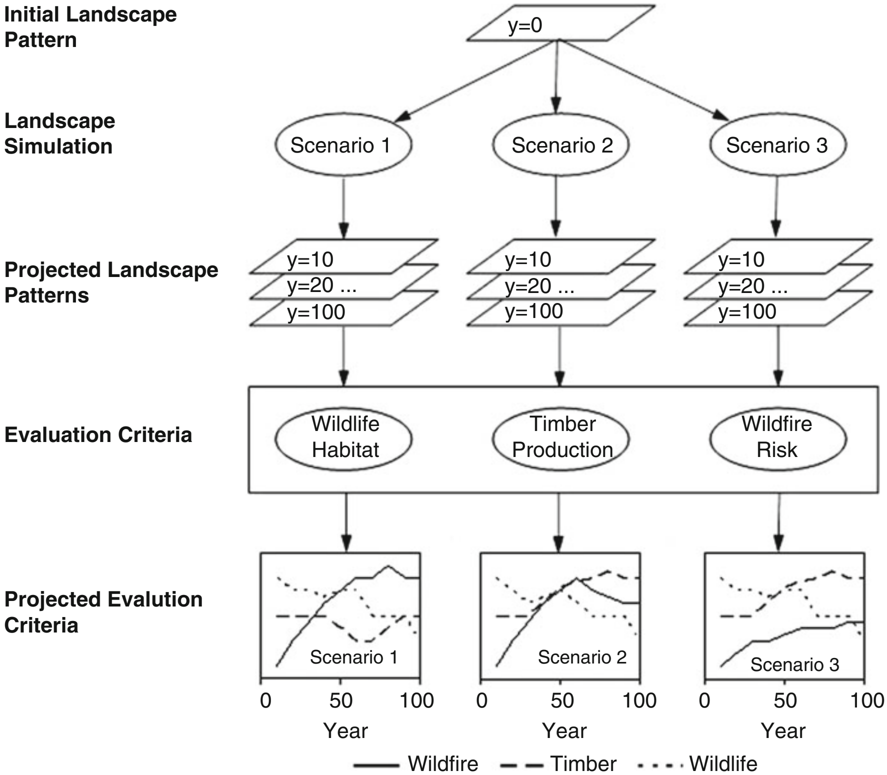

Fig. 6.4 Flowchart illustrating the process of modeling alternative future scenarios. Starting with the current landscape configuration, change is simulated for multiple scenarios based on different forest restoration strategies. The resulting time series of projected landscape configurations are evaluated using a variety of criteria, such as timber production, wildlife habitat suitability, and susceptibility to wildfire

for multiple processes including the death of trees from competition and natural disturbances, the removal of trees through management activities, growth of trees, decay of snags and logs, and the establishment of new trees through either planting or natural regeneration. Because of these characteristics, the output of LAMPS can be linked with detailed habitat suitability models that are based on size distributions of live and dead trees and the spatial arrangement of various stand types across the landscape (McComb et al. 2007; Spies et al. 2007b).

The outcomes of these types of alternative future assessments are dependent on the variety of scenarios that are examined. Two scenarios of particular interest were increasing the number of residual trees left following timber harvests on private lands, and eliminating the practice of thinning young forest plantations on federal lands (Johnson et al. 2007; Spies et al. 2007b). Both scenarios were considered to be realistic policy alternatives that could potentially be implemented through changes to the Oregon Forest Practices Act (affecting private and state lands) or the Northwest

Forest Plan (affecting federal lands). These two alternatives were compared to a baseline scenario that modeled a continuation of current forest management policies across all ownerships. Distributions of forest classes based on tree sizes and hardwood/conifer composition were similar under the baseline and the two alternative scenarios (Spies et al. 2007b). The projected area of old-growth forests in the Coast Range was not sensitive to either of the alternative policies, nor was the projected area of suitable habitat for late-successional species such as the northern spotted owl, the marbled murrelet, and the Pacific fisher (McComb et al. 2007; Spies et al. 2007b). However, habitat for several other species such as the western bluebird, the red tree vole, the olive-sided flycatcher, and the pileated woodpecker was higher under the scenario with increased live-tree retention following timber harvest on private lands. Overall, the results of the analyses indicated that modification of forest management practices on private lands has a greater potential to increase habitat for sensitive species than applying additional restrictions to timber harvesting on the federal lands.

Although there are important differences between the processes of wildfire disturbance and timber harvesting, forest management activities can emulate certain effects of fire and other natural disturbances (Perera et al. 2004). Another study of alternative future scenarios in the Oregon Coast Range used a broader range of forest policy scenarios aimed at restoring various aspects of the historical fire regime (Thompson et al. 2006). The alternatives included increased retention of live trees following timber harvest to emulate the variable severity of historical wildfires, increased rotation lengths to emulate the frequency of historical wildfires, and increased aggregation of harvest units to emulate the size distribution of historical wildfires. When comparing this set of scenarios, increasing live tree retention had a relatively small effect on the distribution of major forest structure classes. In contrast, lengthening the harvest rotation resulted in a significant reduction in the amount of early-successional forests, coupled with an increase in the amount of mature forests. Although it is unlikely that any of these "extreme" forest policy scenarios would be implemented exactly as modeled, they are still valuable for exploring the bounds of what could possibly be achieved by forest restoration efforts over the next century.

6.3.2 Strategies for Managing Forest Landscape Disturbances

Maintaining fire-dependent forest types while also reducing the landscape-wide risk of wildfire by managing the landscape mosaic of forest conditions is an important goal for federal land managers, but is difficult to achieve. Furthermore, public forests are inevitably surrounded by other lands over which agency managers have no control. Fire risk abatement on multi-owner landscapes containing flammable but fire-dependent ecosystems epitomizes the complexities of managing public lands. The LANDIS (LANdscape DIsturbance and Succession) model was used to evaluate the relative effectiveness of four alternative fire mitigation strategies on

the Chequamegon-Nicolet National Forest (Wisconsin, USA), where fire-dependent pine and oak systems overlap with a rapidly developing wildland urban interface (WUI) (Sturtevant et al. 2009). The potential fire-risk mitigation strategies included: (1) ban debris burning (i.e., reduce fire ignition rate by 25%); (2) reduce fire ignition rates by removing understory conifers next to roads on federal lands; (3) placement of permanent firebreaks within fire-prone land types; and (4) redistribution of "risky" management treatments (i.e., those establishing pine or oak) to areas of the National Forest >1 km from housing developments (WUI). Of the risk mitigation strategies evaluated, reduction of ignitions caused by debris-burning had the strongest influence on fire risk, followed by the strategic redistribution of risky forest types away from the high ignition rates of the WUI. Other treatments (fire breaks and reducing roadside ignitions) were less effective. Simulations also showed that some form of active management is required for long-term maintenance of fire-dependent communities (i.e., pine and oak), which also represent the greatest fire risk to homes in the WUI.

Multiple global changes such as timber harvesting in areas previously undisturbed by cutting and climate change will undoubtedly affect the composition and spatial distribution of boreal forests, which will in turn affect the ability of these forests to retain carbon and maintain biodiversity. To reliably predict future states of the boreal forest it is necessary to understand the complex interactions among forest regenerative processes (succession), natural disturbances (e.g., fire, wind and insects) and anthropogenic disturbances (e.g., timber harvest). LANDIS was used to simulate various scenarios of global change on forest composition, biomass (carbon) and landscape pattern in south-central Siberia (Gustafson et al. 2010). Scenarios simulated included: (1) current climate and disturbance (HRV); (2) current climate plus timber harvest; (3) future climate (as predicted by the Hadley Global Circulation Model); (4) future climate plus outbreaks of the Siberian silk moth (currently climate limited); and (5) future climate plus timber harvest and silk moth outbreaks.

Most response variables were more strongly influenced by timber harvest and insect outbreaks than the direct effects of climate change. Direct climate effects generally increased tree productivity and modified the probability of species establishment, but indirect effects on the fire regime generally counteracted the direct effects of climate on forest composition. Harvest and insects significantly produced changes in forest composition, reduced living biomass and increased forest fragmentation. The study concluded that global change is likely to significantly change forest composition of central Siberian landscapes, with some changes taking ecosystems outside the historical range of variability. However, the direct effects of climate change in the study area are not as significant as the exploitation of virgin forest by timber harvest and the potential increased outbreaks of the Siberian silk moth. Novel disturbance by timber harvest and insect outbreaks may greatly reduce the aboveground live biomass of Siberian forests, and may significantly alter ecosystem dynamics and wildlife populations by increasing forest fragmentation.

6.4 Understanding How Landscapes Change

The previous two sections outlined model applications where a major goal is to make realistic predictions of historical or future landscape conditions within a particular landscape. Landscape models can also be applied in a more generalized experimental framework, with an objective of exploring hypotheses about landscape pattern-process relationships (Fahrig 1991). Forest ecosystems often exhibit strong feedbacks in which disturbances influence the spatial pattern of vegetation, and vegetation pattern in turn constrains fire spread and fire effects. Computer simulation models are particularly valuable for understanding these systems because they can be used to project the outcomes of complex interactions, and allow the modeler to observe outcomes that they may not otherwise have been foreseeable (Rykiel 1996). Creating a landscape model requires development of a conceptual framework for representing the forest landscape, specification of mathematical equations and rule sets for modeling interactions between system components, and estimation of the parameters that control these interactions. Based on user-supplied inputs, the computer performs bookkeeping and computational tasks to track the multitude of state variables over space and time. Therefore, landscape simulation models can be used as “assumption analyzers” that allow scientists to see how their understanding of environmental gradients, fire regimes, and forest succession plays out over large areas and long time frames (Bart 1995).

This approach to landscape simulation modeling is primarily an explanatory or heuristic exercise, where the overarching objective is to enhance understanding of complex pattern-process interactions (Peck 2004; Perry and Millington 2008). In comparison to the more predictive, scenario-based modeling approaches described in the previous section, heuristic modeling applications tend to be less realistic but have greater generality. For example, landscape models may be applied using hypothetical scenarios that would not be considered plausible alternative futures (e.g., the elimination of human influences and the restoration of historical disturbance regime). Model implementation is often carried out using artificial landscapes and may involve complex experimental designs rather than comparisons of a limited number of scenarios. These generalizations are analogous to the simplifications that are necessary when carrying out a laboratory or field experiment (Caswell 1988). Although the results of heuristic exercises are usually not directly applicable to specific landscape restoration projects, the more general knowledge gained may become an important part of the underlying science that is applied in developing landscape restoration approaches.

6.4.1 Disturbance Regimes and Landscape Patterns

DISPATCH is a GIS-based model that was developed to simulate the spread of disturbances across forested landscapes and the resulting changes in landscape patterns (Baker et al. 1991). The model was applied to study the effects of changing

fire regimes in the Boundary Waters Canoe Area (BWCA) in Minnesota using a simplified framework for modeling disturbances and landscape dynamics (Baker 1992, 1993, 1994). Fires were all assumed to be stand-replacing and landscape patterns were modeled as age classes reflecting time since the most recent fire. Rather than replicating the exact patterns of environmental variability in the BWCA, DISPATCH was run on a homogeneous, rectangular landscape that had an area equal to that of the BWCA. Because of these simplifying assumptions it was not possible to link model results back to actual locations within the BWCA. However, the simplified modeling framework made it possible to generalize the results of landscape-level simulation experiments to other landscapes with similar disturbance regimes and successional pathways.

DISPATCH was used in several studies that compared alternative scenarios that considered different temporal patterns of changes in disturbance regimes (Baker 1992, 1993, 1994). The *historical* scenario combined fire regimes from three time periods when fire return intervals in the BWCA remained relatively constant: The pre-settlement period (AD 1368–1867), the settlement period (AD 1868–1910), and the suppression period (AD 1911-present). The *pre-settlement* scenario utilized the fire regime from the pre-settlement period for the entire 1,000-year simulation. The *restoration* scenario was the same as the historical scenario through 1993, at which time the fire return intervals were reset to pre-settlement levels to simulate restoration of the historical fire regime. Another study used DISPATCH to examine climate change scenarios that affected fire return intervals and fire sizes, fragmentation and restoration scenarios that considered changes in disturbance regimes resulting from forest management, and the effects of alternative landscape configurations at the beginning of the simulation (Baker 1995). A variety of landscape metrics, including mean pixel age, mean patch size, mean shape, mean fractal dimension, Shannon diversity index, mean richness, fraction of old growth, and mean angular second moment, were used to evaluate the effects of these scenarios on landscape structure.

These simulation experiments led to a number of general hypotheses about how forest landscapes respond to changes in disturbance regimes. Landscape structure does not respond immediately to an altered disturbance regime, but requires a period of time for the new regime to overwrite existing patterns and generate a new quasi-equilibrium. In general, landscape composition (e.g., Shannon's diversity index) responds more rapidly to an altered disturbance regime than landscape configuration (e.g., mean patch size) (Baker 1992, 1994). Landscape responses are spatially heterogeneous and scale dependent, with greater variability in response time as landscape extent decreases (Baker 1993). The time lag in landscape response is also contingent upon the disturbance regime and landscape patterns prior to the change, and whether the change results in increased or decreased rates and sizes of disturbances. For example, simulation experiments demonstrated that landscapes with lower patch densities responded more quickly than landscapes with higher patch densities (Baker 1995). Landscape structure also responded more quickly to climate warming scenarios in which fire frequency and size increased than to cooling scenarios in which fire frequency and size decreased. Landscapes typically adapted

to new disturbance regimes within 0.5–2 fire rotations, suggesting that human activities or natural processes that change fire frequency cause landscape structure to exist in a constant state of disequilibrium with the disturbance regime because of these long response times.

6.4.2 Landscape Dynamics in the Oregon Coast Range

A more recent study used landscape simulation models to examine whether restoration of historical disturbance processes would be an effective strategy for restoring pre-settlement landscape patterns in the Oregon Coast Range (Nonaka and Spies 2005). Starting with the landscape configuration in 1996, two scenarios were simulated. The first scenario assumed a continuation of current forest management practices that were simulated using the LAMPS model. The second scenario assumed that no forest management would take place and pre-settlement fire regimes would be restored, with wildfire patterns simulated using the LADS model. Continuation of current land management practices for 100 years moved landscape patterns toward the HRV, but did not completely restore all aspects of the pre-settlement landscape patterns. Restoration of the historical disturbance regime initially increased the departure of landscape patterns from pre-settlement conditions, and still required several centuries to create patterns falling within the HRV. These results supported the main conclusions of earlier studies applying DISPATCH in the BWCA; landscape patterns may take centuries to respond to changes in the disturbance regime, with different metrics of landscape patterns responding at different rates.

Current forest management policies in the Oregon Coast Range are based on static reserve-based strategies. Late-successional reserves on public lands are projected to be eventually dominated by old forests, whereas private landscapes are expected to remain dominated by younger managed forests (Spies et al. 2007a). In contrast, pre-settlement fire regimes created a continuously shifting mosaic of forest age classes (Wimberly et al. 2000, 2004; Wimberly 2002). To explore the ecological implications of changes in the rates and patterns of landscape dynamics, the LADS model was modified to incorporate a simple species occupancy model. Experimental model runs were conducted for several hypothetical species with a range of dispersal distances, colonization rates, and extinction rates (Wimberly 2006). Experiments were designed to compare dynamic and static landscapes with similar landscape patterns and habitat amounts. Species exhibited a more rapid decline to extinction with habitat loss in dynamic landscapes than in static landscapes. However, in some cases, species occupancy was actually higher in dynamic landscape mosaics than in static landscapes with similar habitat amount and pattern. In these situations, habitat dynamics actually increased habitat connectivity over space and time, even though the habitat pattern at any single point in time was highly fragmented.

6.5 Summary and Conclusions

This review has outlined three examples of how landscape simulation models can be used to support forest landscape restoration. In the first type of application, landscape models of disturbance and forest succession are used to estimate historical variability in landscape composition and configuration based on information about the return intervals, sizes, and severities of historical disturbances. Assessments of the departure of current landscapes from the HRV can be carried out at a range of different scales, from coarse regional assessments to more detailed predictions of the spatial pattern of departure from HRV within individual landscapes. Key challenges in carrying out this type of assessment include selecting ecologically relevant landscape metrics to use in computing HRV and developing appropriate quantitative methods for evaluating the degree of departure from the HRV. Major limitations to this approach include a lack of reliable data on historical fire regimes in some landscapes; a scarcity of detailed information about historical landscapes patterns that could be used to validate model-based HRV estimates; and the fact that climate change, species invasions, and other human impacts have the potential to create novel ecosystems that have no historical analogue (Hobbs et al. 2006). Despite these limitations, evaluating departure of the current landscape from the HRV is an important starting point for assessing forest landscape restoration alternatives.

Another common application of landscape simulation models is to project future landscapes under alternative landscape restoration scenarios. One of the most crucial elements of this type of assessment is the number and characteristics of the scenarios that are examined. Often a relatively small number of scenarios are considered, and the scenarios are selected to be realistic representations of plausible forest restoration strategies. However, there may be other, more effective strategies that are outside the solution space of the chosen scenarios. Conclusions about the potential effects of forest landscape restoration activities may also depend upon the amount of variability among the alternatives considered. Scenarios that consider only minor modifications to current silvicultural practices will likely have only a minor effect on landscape structure and wildlife habitat when compared to a "business as usual" scenario. In contrast, examining a wider range of alternatives, including possible climate change effects, can help to outline the possible range of future landscape conditions. Validating the projections of landscape simulation models over time scales of decades to centuries remains a major challenge (Rykiel 1996; He 2008). However, the absolute accuracy of model predictions may be less important than the ability to realistically portray the relative effects of different scenarios.

Simulation experiments with landscape models focus less on making predictions of historical or future landscape conditions, and place more emphasis on exploring general hypotheses about pattern-process relationships. For example, simulation experiments may examine purely hypothetical scenarios such as the restoration of historical fire regimes across large landscapes (Baker 1992, 1993, 1994; Nonaka and Spies 2005), or consider a wide range of disturbance scenarios, initial conditions, and other parameter settings (Baker 1995; Wimberly 2006). Important insights gained from these studies include the recognition that changes in landscape composition

and configuration lag behind shifts in disturbance regimes, and that temporal as well as spatial landscape heterogeneity is important to consider when assessing ecological responses to changing disturbance regimes. The general knowledge gained from these experiments can contribute to the conceptual foundation for developing forest restoration strategies, or can serve as a basis for developing more detailed and realistic alternative scenario assessments.

Literature Cited

Allen CD, Savage M, Falk DA, Suckling KF, Swetnam TW, Schulke T, Stacey PB, Morgan P, Hoffman M, Klingel JT (2002) Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecol Appl 12:1418–1433

Baker WL (1989) A review of models of landscape change. Landsc Ecol 2:111–133

Baker WL (1992) Effects of settlement and fire suppression on landscape structure. Ecology 73:1879–1887

Baker WL (1993) Spatially heterogeneous multiscale response of landscapes to fire suppression. Oikos 66:66–71

Baker WI (1994) Restoration of landscape structure altered by fire suppression. Conserv Biol 8:763–769

Baker WL (1995) Longterm response of disturbance landscape to human intervention and global change. Landsc Ecol 10:143–159

Baker WL, Egbert SL, Frazier GF (1991) A spatial model for studying the effects of climatic change on the structure of landscapes subject to large disturbances. Ecol Model 56:109–125

Bart J (1995) Acceptance criteria for using individual-based models to make management decisions. Ecol Appl 5:411–420

Bettinger P, Lennette M, Johnson KN, Spies TA (2005) A hierarchical spatial framework for forest landscape planning. Ecol Model 182:25–48

Bu R, He HS, Hu YM, Chang Y, Larsen DR (2008) Using the LANDIS model to evaluate forest harvesting and planting strategies under possible warming climates in Northeastern China. For Ecol Manag 254:407–419

Cairns DM, Lafon CW, Waldron JD, Tchakerian M, Coulson RN, Klepzig KD, Birt AG, Xi W (2008) Simulating the reciprocal interaction of forest landscape structure and southern pine beetle herbivory using LANDIS. Landsc Ecol 23:403–415

Caswell H (1988) Theory and models in ecology: a different perspective. Ecol Model 43:33–44

Fahrig L (1991) Simulation methods for developing general landscape-level hypotheses of single-species dynamics. In: Turner MG, Gardner RH (eds) Quantitative Methods in Landscape Ecology. Springer, New York, pp 417–442

Forest Ecosystem Management and Assessment Team (FEMAT) (1993) Forest ecosystem management: an ecological, economic, and social assessment. U.S. Departments of Agriculture, Commerce, and the Interior, and the Environmental Protection Agency, Washington, DC

Gustafson EJ, Shvidenko AZ, Sturtevant BR, Scheller RM (2010) Predicting climate change effects on forest biomass and composition in south-central Siberia. Ecol Appl 20:700–715

He HS (2008) Forest landscape models: definitions, characterization, and classification. For Ecol Manag 254:484–498

Hessburg PF, Agee JK, Franklin JF (2005) Dry forests and wildland fires of the inland Northwest USA: Contrasting the landscape ecology of the pre-settlement and modem eras. For Ecol Manag 211:117–139

Hobbs RJ, Arico S, Aronson J, Baron JS, Bridgewater P, Cramer VA, Epstein PR, Ewel JJ, Klink CA, Lugo AE, Norton D, Ojima D, Richardson DM, Sanderson EW, Valladares F, Vila M, Zamora R, Zobel M (2006) Novel ecosystems: theoretical and management aspects of the new ecological world order. Glob Ecol Biogeogr 15:1–7

Hunter ML (1993) Natural fire regimes as spatial models for managing boreal forests. Biol Conserv 65:115–120
Impara PC (1997) Spatial and temporal patterns of fire in the forests of the Central Oregon Coast Range. Oregon State University, Corvallis
Johnson KN, Bettinger P, Kline JD, Spies TA, Lennette M, Lettman G, Garber-Yonts B, Larsen T (2007) Simulating forest structure, timber production, and socioeconomic effects in a multi-owner province. Ecol Appl 17:34–47
Karau EC, Keane RE (2007) Determining landscape extent for succession and disturbance simulation modeling. Landsc Ecol 22:993–1006
Keane RE, Parsons RA, Hessburg PF (2002) Estimating historical range and variation of landscape patch dynamics: limitations of the simulation approach. Ecol Model 151:29–49
Keane RE, Cary GJ, Davies ID, Flannigan MD, Gardner RH, Lavorel S, Lenihan JM, Li C, Rupp TS (2004) A classification of landscape fire succession models: spatial simulations of fire and vegetation dynamics. Ecol Model 179:3–27
Keane RE, Holsinger LM, Pratt SD (2006) Simulating historical landscape dynamics using the landscape fire succession model LANDSUM version 4.0. General Technical Report RMRS-GTR-171CD, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO
Keane RE, Rollins M, Zhu ZL (2007) Using simulated historical time series to prioritize fuel treatments on landscapes across the United States: the LANDFIRE prototype project. Ecol Model 204:485–502
Landres PB, Morgan P, Swanson FJ (1999) Overview of the use of natural variability concepts in managing ecological systems. Ecol Appl 9:1179–1188
Leng WF, He HS, Bu RC, Dai LM, Hu YM, Wang XG (2008) Predicting the distributions of suitable habitat for three larch species under climate warming in Northeastern China. For Ecol Manag 254:420–428
Long CJ, Whitlock C (2002) Fire and vegetation history from the coastal rain forest of the western Oregon coast range. Quat Res 58:215–225
Long CJ, Whitlock C, Bartlien PJ, Millspaugh SH (1998) A 9,000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Can J For Res 28:774–787
McComb BC, Spies TA, Olsen KA (2007) Sustaining biodiversity in the Oregon Coast Range: potential effects of forest policies in a multi-ownership province. Ecol Soc 12(2):29
Nassauer JI, Corry RC (2004) Using normative scenarios in landscape ecology. Landsc Ecol 19:343–356
Nonaka E, Spies TA (2005) Historical range of variability in landscape structure: a simulation study in Oregon, USA. Ecol Appl 15:1727–1746
Nonaka E, Spies TA, Wimberly MC, Ohmann JL (2007) History range of variability (HRV) in live and dead wood biomass: a regional-scale simulation study. Can J For Res 37:2349–2364
Peck SL (2004) Simulation as experiment: a philosophical reassessment for biological modeling. Trends Ecol Evol 19:530–534
Perera AH, Buse LJ, Weber MG, Crow TR (2004) Emulating natural forest landscape disturbances: a synthesis. In: Perera AH, Buse LJ, Weber MG (eds) Emulating natural forest landscape disturbances. Columbia University Press, New York, pp 265–274
Perry GLW, Enright NJ (2002) Humans, fire and landscape pattern: understanding a maquis-forest complex, Mont Do, New Caledonia, using a spatial 'state-and-transition' model. J Biogeogr 29:1143–1158
Perry GLW, Enright NJ (2006) Spatial modelling of vegetation change in dynamic landscapes: a review of methods and applications. Prog Phys Geogr 30:47–72
Perry GLW, Millington JDA (2008) Spatial modelling of succession-disturbance dynamics in forest ecosystems: concepts and examples. Perspect Plant Ecol Evol Syst 9:191–210
Peterson GD, Cumming GS, Carpenter SR (2003) Scenario planning: a tool for conservation in an uncertain world. Conserv Biol 17:358–366
Rollins MGC, Frame K (2006) The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. General Technical Report RMRS-GTR-175, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO
Rykiel EJ (1996) Testing ecological models: the meaning of validation. Ecol Model 90:229–244

Scheller RM, Mladenoff DJ (2005) A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. Glob Chang Biol 11:307–321

Scheller RM, Mladenoff DJ (2007) An ecological classification of forest landscape simulation models: tools and strategies for understanding broad-scale forested ecosystems. Landsc Ecol 22:491–505

Schmidt KM, Menakis JP, Hardy CC, Hann WJ, Bunnell DJ (2002) Development of coarse-scale spatial data for wildland fire and fuel management. General Technical Report RMRS-87, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO

Schumacher S, Bugmann H (2006) The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. Glob Chang Biol 12:1435–1450

Shifley SR, Thompson FR, Dijak WD, Larson MA, Millspaugh JJ (2006) Simulated effects of forest management alternatives on landscape structure and habitat suitability in the Midwestern United States. For Ecol Manag 229:361–377

Society for Ecological Restoration International Science & Policy Working Group (2004) The SER International Primer on Ecological Restroation. Society for Ecological Restoration International, Tucson

Spies TA, Johnson KN, Burnett KM, Ohmann JL, McComb BC, Reeves GH, Bettinger P, Kline JD, Garber-Yonts B (2007a) Cumulative ecological and socioeconomic effects of forest policies in Coastal Oregon. Ecol Appl 17:5–17

Spies TA, McComb BC, Kennedy RSH, McGrath MT, Olsen K, Pabst RJ (2007b) Potential effects of forest policies on terrestrial biodiversity in a multi-ownership province. Ecol Appl 17:48–65

Steele BM, Reddy SK, Keane RE (2006) A methodology for assessing departure of current plant communities from historical conditions over large landscapes. Ecol Model 199:53–63

Sturtevant BR, Miranda BR, Yang J, He HS, Gustafson EJ, Scheller RM (2009) Studying fire mitigation strategies in multi-ownership landscapes: calancing the management of fire-dependent ecosystems and fire risk. Ecosystems 12:445–461

Teensma PD, Rienstra JT Yeiter MA (1991) Preliminary reconstruction and analysis of change in forest stand age class of the Oregon Coast Range from 1850 to 1940. T/N OR-9, U.S. Bureau of Land Management, Portland, OR

Thompson JR, Johnson KN, Lennette M, Spies TA, Bettinger P (2006) Historical disturbance regimes as a reference for forest policy in a multiowner province: a simulation experiment. Can J For Res 36:401–417

Urban DL, O'Neill RV, Shugart HH (1987) Landscape ecology: a hierarchical perspective can help scientists understand spatial patterns. Bioscience 37:119–127

Weisberg PJ, Swanson FJ (2003) Regional synchroneity in fire regimes of western Oregon and Washington, USA. For Ecol Manag 172:17–28

Wimberly MC (2002) Spatial simulation of historical landscape patterns in coastal forests of the Pacific Northwest. Can J For Res 32:1316–1328

Wimberly MC (2004) Fire and forest landscapes in the Georgia Piedmont: an assessment of spatial modeling assumptions. Ecol Model 180:41–56

Wimberly MC (2006) Species dynamics in disturbed landscapes: when does a shifting habitat mosaic enhance connectivity? Landsc Ecol 21:35–46

Wimberly MC, Kennedy RSH (2008) Spatially explicit modeling of mixed-severity fire regimes and landscape dynamics. For Ecol Manag 254:511–523

Wimberly MC, Ohmann JL (2004) A multi-scale assessment of human and environmental constraints on forest land cover change on the Oregon (USA) Coast Range. Landsc Ecol 19:631–646

Wimberly MC, Spies TA, Long CJ, Whitlock C (2000) Simulating historical variability in the amount of old forests in the Oregon Coast Range. Conserv Biol 14:167–180

Wimberly MC, Spies TA, Nonaka E (2004) Using criteria based on the natural fire regime to evaluate forest management in the Oregon Coast Range of the United States. In: Perera AH, Buse LJ, Weber MG (eds) Emulating Natural Forest Landscape Disturbances. Columbia University Press, New York, pp 146–157